PULSED CONVECTION: THE MAKING OF CHONDRULES. C. E. KenKnight, Minneapolis MN, kenk@physics.spa.umn.edu

W. Cabot [1] simulated convection in a disk with opacity due to small grains and confirmed the modal analysis of Ruden et al. [2]. Given a source of heat near the midplane, the gas responds by organizing itself into "hula hoops" which are centered on the midplane and flow through it. Adjacent hoops twist oppositely so that friction is small. Given thermal aggregation (random walk and touching) of the grains, the system is apt to develop local brief heating events which restructure or melt the aggregates and make the system inhomogeneous in opacity. Settling of the larger solids (chondrules) concentrates solids in a ringlet centered in each hoop. I show that several chemical reactions are able to furnish the grain heating. Study is needed of a supersonic vortex obstructed at its center by a granular, compressible medium.

The nebular opacity has the unfamiliar property that it increases with the local temperature T. This is because most of the dust grains are much smaller than the (peak) wavelength of the heat which it is containing. If T rises, then the radiation "resolves" the grains better and interacts more strongly. Given a source of heat near the midplane, the gas forms vortices. Like all smoke rings, the vortices have the property that they tend to keep within them any particles caught when they formed. The flow rises about 1 thermal scale height h, cools by radiating to space in a horizontal flow for length h, then plunges back to and through the midplane. There it somehow causes a new heat release if the motion is to continue. Energy is available if the perturbed gas drifts toward the forming Sun. The convection loop is a classical heat engine. It takes in heat at the hot terminal and delivers it as z = +h or –h. The nature of the heating event has not been known.

Larimer [3, p. 1221] noted that at 2000°K the dissociation reaction of hydrogen has the equilibrium constant $K = p(H_2)/p^2(H) = 10^{5.6}$. Thus at half dissociation the partial pressures of the atoms and molecules of hydrogen are each $10^{-5.6}$ bar, for a total pressure of 5 μbar, close to that of the midplane pressure of a minimum mass nebula. Thus one must consider whether the chondrule heating events involved the presence of appreciable atomic hydrogen. Draining available dinetic energy from the gas phase to dissociate molecules makes the local pressure drop, say in volume "V." If this happens near the midplane more quickly than 1/3 of a local year, the pressure support for the columns of gas above that location V drops. The columns of gas fall slowly after such a brief loss of support, but if the perturbation is repeated each time that V passes through the midplane, then the falling of the columns can furnish a heavy piston to drive the local temperature to a high value. We will argue that 1) heating events make the heat engine transfer more heat, 2) tend to repeat at or near the location V, and 3) cause solids to concentrate in a core of the vortex (a ringlet of solids).

Levy [4] posed two problems of chondrule-making: a) power enough to melt the chondrules quickly and b) power enough to make chondritic planets. The second problem was understated. If we suppose that the needed energy to make Earth comes from an inward motion of all the gas which was circulatized after arriving in the vicinity of a = 1 AU, $E = (GMm/2a)(\Delta a/a)$, where $\Delta a = a(1.2–0.85)$ and m is the gas mass associated with an Earth mass, $6/f \times 10^{27}$ g and f = 1/300 is the dust to gas ratio by mass. Although this gas mass is nearly a Jupiter mass, the available power is so low if spread out over about 1 m.y. that the surface temperature of the nebula is much lower than previous estimates. Setting E equal to the black body radiation lost from the surface over a time interval t, $E = 2\sigma T_s^4 (2\pi a)(0.35a)t$, we can set an upper limit for the product $T_s^4 t$: $(T_s/100°K)(t/1\ m.y.)^{1/4} < 0.356$. If chondrule-making requires some of this energy, then the surface temperature T_s must have been, on the average, less than about 35°K in the vicinity of 1 AU. The estimate is quite robust since both t and E enter only to a 0.25 power. We can also say that the chondrule-making process must have taken place at great optical depth (well below the nebular surface) in order to avoid losing too much power. In what follows I will assume a midplane T of about 200°K, in keeping with this low value for the surface temperatue. Results are not sensitive to the assumption.

Next we shall show that hydrogen dissociation (and some other chemical reactions) is easily able to cause chondrule melting, problem a). Typical values for the midplane pressure P, scale height h, density ρ for a minimum mass nebula at 1 AU are given in Table 1 in terms of an assumed T of 200°K, a mean molecular weight of 2.2, and a gas surface densitym, Σ which again assumes an Earth mass spread from 0.85 to 1.2 AU. For a species whose frequency relative to hydrogen is q, the energy flux to the surface is independent of the assumed nebular temperature, but the Keplerian angular frequency Ω decreases like $a^{-3/2}$ and the surface density Σ decreased as least like $a^{-3/2}$ with increasing a. Thus ar a = 2 AU the midplane pressure P is about 3 μbar. For recombination of H atoms on a surface the avilable energy is about 10 eV per 2 atoms. At half dissociation we have q = 0.5; the power which is incident on a surface approaches 1.2E+8 erg/cm^2-s. Yet, this energy flux is too large because we know the chondrule cooling duration was of the order of 1000 s; the energy dose to a chondrule whose diameter D is 0.1 cm is 250.E+10 ergs/g, whereas only about 1.E+10 ergs/g are needed to melt it. For matrix fines the excess of available energy is 1000 times worse; fines caught in a heating event in which hydrogen is half dissociated would quickly vaporize. Chondrules can resist by radiating as a black body and by developing a surface on which the efficiency for reaction is low.

Other chemical reactions on a surface which are apt to be interesting are recombination of CO with the aid of H_2 to yield an amorphous carbon layer plus water vapor. The energy per molecule incident is near 1 eV, but the carbon layer becomes refractory and resistant to attack. Even condensation of vapors to give refractory solids are of interest, E_o is apt to be about 0.5 eV. In a cosmic gas the corresponding frequencies q are about 1/100 at most. But when solids are concentrated 1000 times, those frequencies q approach unity.

Finally, the amount of heat transferred by the convection loop will increase if the heating event changes aggregates of grains from matrix size fines to chondrule size. The latter constitute "dark matter" which makes a small contribution to the opacity. Forming them aids cooling if they are lofted near the nebula surface. The aggregation and settling of dust grains in a minimum mass nebula was studied in [5]. They showed that chondrules would settle a distance h in a few hundred years—not the half a local year needed for a resonance between clearing a solids after a heating event and the next one. However, their equation 15 shows that chondrules would settle through a cloud of (unprocessed) fines and grow appreciably in half a local year if the dust-to-gas ratio were enhanced by 1000 times. This is evidently the style of growth for ordinary chondrites for which multiple rims are known. Rims tend to be enriched in elements (like Si and Fe which are rejected from forsterite-rich olivine) and exposed to corrosion at the chondrule surface. The carbonaceous chondrites used another mode of growth [6]. According to equation 20 of [5], the sizes of fractal aggregates whose dimensionality D is less than 2 grow much more rapidly with time than solid sphere. These low-dimensionality aggregates happen if the growth includes needlelike features. If the needles were due to water frost grown during the cooling part of the convection cycle near the cold nebular surface, then 1) sublimation of the needles during a heating event caused restructuring and collapse of the aggregates as required for enhancing the convective heat engine and 2) the high local concentration of H_2O around the fines assured highly oxidizing (corrosive) conditions during the heating event.

References: [1] Cabot W. (1996) *Astrophys. J., 465*, 874–886. [2] Ruden S. P. et al. (1988) *Astrophys. J., 329*, 739–763. [3] Larimer J. W. (1967) *GCA, 31*, 1215–1238. [4] Levy E. H. (1988) in *Meteorites and the Early Solar System*, 700. [5] Weidenschilling S. J. et al. (1989) in *The Formation and Evolution of Planetary Systems*, 131–146. [6] Grossman J. N. and Wasson J. T. (1983) in *Chondrules and Their Origis*, 88–121.

Table 1

Quantity	Expression	Value
f	dust/gas ratio, by mass	1/300
Ω	2π / 1 local year	2.E-7
c	SQRT(8RT/πM)	1.39E+5
fΣ	1 Earth mass in 0.35 AU	12 g/cm^2
h	hΩ = c SQRT(π/4)	0.62E+12 cm
P	pressure P = $\Omega\sigma$c/4	25.E-6 bar
ρ	density Σ / h / SQRT(π)	3.3E-9 g/cc
J	flux q$\Sigma\Omega$N / 2πM	qN 5.3E-5
qJE_o	energy flux to surface	qE_o(eV) 5.E+7
CT	energy/gm to melt	1.E+10
A/m	area/mass 6 / ρ_sD	20 cm^2/g